Pergamon

0042-6989(95)00024-0

Vision Res. Vol. 35, No. 17, pp. 2491–2502, 1995

0042-6989/95 $9.50 + 0.00

Microfluctuations of Steady-state Accommodation and the Cardiopulmonary System

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Received 21 July 1993; in revised form 18 July 1994; in final form 20 January 1995

The relationship between variations in steady-state accommodation (microfluctuations) and rhythmic cycles in cardiopulmonary system was investigated. As previously reported, vascular pulse frequency was consistently correlated with the high frequency component of steady-state accommodation microfluctuations. In a new finding, respiration rate and an associated cycle in the instantaneous pulse rate also showed a correlation with a low frequency component of the accommodation power spectra. This apparent coherence between respiration frequency and an accommodation low frequency component was maintained during rapid breathing and was evident at the expected frequency during regulated breathing patterns. This association may reflect the direct influence of the autonomic nervous system upon the ciliary muscle or may be caused by the modulation of intraocular pulse by the autonomic nervous system.

Accommodation Microfluctuations Steady-state Pulse Respiration

INTRODUCTION

Microfluctuations occur in the accommodation response during steady-state viewing conditions. These microfluctuations are typically <0.25 D in magnitude and occur at frequencies <2 Hz. The temporal frequencies of the microfluctuations have been further classified into high (1–2 Hz) and low (<0.6 Hz) frequency components (Charman & Heron 1988; Winn & Gilmartin, 1992). The potential role, if any, of the high and low frequency components of microfluctuations is not clear.

A significant correlation between high frequency microfluctuations and arterial pulse was first demonstrated by Winn, Pugh, Gilmartin and Owens (1990a). This relationship was maintained during the recovery phase of exercise-induced increase in pulse rate and was absent in the aphakic eye of unilateral aphakes. Winn, Pugh, Gilmartin and Owens (1990b) also found that the central and peripheral regions of the crystalline lens exhibited similar microfluctuations in terms of frequency peaks but were diminished in amplitude in the periphery compared with the central lens.

Since vascular pulse appears to influence accommodation microfluctuations, we examined the association between rhythms within the cardiopulmonary system and the various rhythms constituting the microfluctuations of steady-state accommodation. This was achieved by simultaneously sampling steady-state accommodation, carotid artery pulse and respiratory cycles. Since pulse rate varies under the influence of the autonomic nervous system through factors such as respiration (sinus arrhythmia), we therefore analysed pulse rate in terms of instantaneous pulse rate (i.e. heart rate variability). The variability of the heart rate has been widely used in the study of the influence of the autonomic nervous system on the cardiopulmonary system (e.g. Angelone & Coulter, 1964; Hirsch & Bishop, 1981; Bernston, Cacioppo & Quigley, 1993). We then used the spectral characteristics of the accommodation, pulse, instantaneous pulse rate and respiration signals to investigate the potential associations between accommodation microfluctuations and rhythms within the cardiopulmonary system.

METHODS

Accommodation measurement technique

Measurements of accommodation response were made with a modified Canon Autoref R-1, which is an infrared optometer that allows free-space viewing. Pugh and Winn (1988, 1989) described the modifications to convert the Autoref R-1 from an instrument capable of single static measures of the eye's refractive status, to an instrument capable of both static measures and continuous voltage output, which can be directly related to the continuous accommodative status of the subject.

In the continuous mode of operation, the Autoref R-1

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was calibrated to give an output d.c. voltage level dependent upon the accommodative state of the subject. Our data acquisition system consists of a computer, a parallel input/output board to acquire the static data, and a 12-bit analogue-to-digital (A-to-D) converter board to acquire both the static shot waveforms and the continuous signal. The details of our calibration methods are presented in Davis, Collins and Atchison (1993). An individual calibration was performed for each subject tested.

During the following experiments the pupil of the subject's right eye was dilated with one drop of 0.4% benoxinate followed by two drops of 2.5% phenylephrine, prior to testing. Phenylephrine is a sympathomimetic which dilates the pupil without substantially affecting the accommodation amplitude (Mordi, Lyle & Mousa, 1986) and the concentration which we used should not have significantly influenced the cardiopulmonary system. The dilated pupil size was always >5 mm, since the Autoref R-1 output signal is diminished when pupil size falls below 4 mm (Winn, Pugh, Gilmartin & Owens, 1989a; Davis *et al.*, 1993). The subject's left eye was not occluded during testing. Therefore we were measuring accommodation response from the subjects' right eyes during binocular viewing, to ensure that testing conditions were as close as possible to natural binocular viewing conditions.

Subjects were positioned in the Canon Autoref R-1 using a bite-bar, brow bar, and head strap to minimize head movements. The head restraint apparatus was mounted separately to the body of the Autoref R-1 and was damped, to minimize the transfer of body vibrations to the Autoref R-1. A 40 sec accommodation record was measured for the right eye of each subject as they binocularly viewed a letter chart of high contrast (70%), internally illuminated (average luminance of 170 cd/m^2) at a distance of 50 cm (2 D demand). Letter size subtended 7 min arc. The subjects were instructed to keep the fixated letter "as clear as possible" and to blink whenever necessary. Room illumination was low photopic (50 lx). All subjects gave informed consent before participating in the study.

Pulse and respiration measurement technique

During the measurement of accommodation, the subjects' pulse and respiration rate were simultaneously monitored using sensitive microphones. The microphone to detect pulse rate was enclosed in the cup of a stethoscope and firmly taped over the external carotid artery on the right side of the neck. The microphone to measure respiration was attached to an adjustable probe and positioned just below a nostril. The signals from both the pulse and respiration microphones were fed into two separate channels of the A-to-D board, also used to acquire the accommodation signal. Appropriate gain settings were made through the software used to operate the A-to-D board. Control experiments were conducted to ensure no leakage of signals between the three A-to-D channels. An example of the three signals (accommodation, pulse and respiration) for subject AG is presented in Fig. 1.

Normal pulse rate is known to vary under the influence of various cardiopulmonary rhythms, such as respiratory sinus arrhythmia (Bernston *et al.*, 1993). This variability in heart rate can be assessed through the instantaneous pulse rate, which is derived from the delay between consecutive heart beats (see Fig. 1). Since Winn *et al.* (1990a) had demonstrated a significant correlation between high frequency accommodation microfluctuations and arterial pulse, it was therefore possible that rhythms in the subjects' pulse rate would also be evident within their accommodation microfluctuations, so we derived the instantaneous pulse rate from each pulse record we acquired.

Power spectrum analyses

We sampled the accommodation, pulse and respiration signals at a frequency of 25.6 Hz (to give 1024 data points in a 40 sec record), which was well above the Nyquist frequency. The Nyquist frequency is twice the highest frequency of interest in the signal, and in the case of accommodation signals this highest frequency should not normally exceed 2–2.5 Hz (Pugh, Eadie, Winn & Heron, 1987).

To analyse the cyclic changes in the acquired signals (accommodation, pulse, instantaneous pulse and respiration), a fast Fourier transform (FFT) was employed and a power spectrum derived from the FFT. The power spectrum gives the square of the amplitude of the cyclic changes vs their temporal frequency (Hz). We routinely applied a hamming window in the power spectrum analyses.

The temporal resolution of the power spectrum is a function of the sampling time ($1/t$). For example with a 10 sec accommodation sample, the resolution is 0.1 Hz (each frequency bin is 0.1 Hz wide). Most previous analyses of accommodation microfluctuations have been limited to approximately this resolution, since most subjects find it difficult not to blink in a period of longer than 10 sec. To improve resolution of the power spectrum analysis we extended our accommodation sampling time to 40 sec and developed a technique for deleting blink artefacts from the record.

To examine the variability of power spectra derived from accommodation records from the same subject (MS) we recorded three consecutive 40 sec accommodation records under identical conditions. The power spectra derived from each record are presented in Fig. 2. There was a consistent general distribution of peaks within the three power spectra, with some relatively small variations in the peak's amplitude and frequency.

Removing blink artefacts from the accommodation record

Any blink within the continuous sampling time causes an abrupt change in signal amplitude. This rapid change in signal amplitude introduces a substantial increase in power spectrum amplitude across a range of temporal frequencies, dependent upon factors such as the characteristics and frequency of the blink artefacts within the

signal. Within a 40 sec steady-state accommodation record we typically found subjects would blink 4–6 times.

To remove the blink artefact from the accommodation record, we located the beginning and end of the blink artefact within the accommodation record and deleted the intervening data points from the record. The time span of normal blinks is about 250 msec (Doane, 1980). We then counted back 15 data points (about 600 msec) from the beginning of the blink and forward 15 data points from the end of the blink and mathematically interpolated between these points using a cubic polynomial function.

This interpolation technique was effective because the time span of blinks was small compared with the frequency of normal microfluctuations of accommodation. During this study we did not use any accommodation sample with more than eight blinks in the 40 sec sampling period. Eight blinks during a 40 sec accommodation record required 2.0 sec (5%) of interpolated

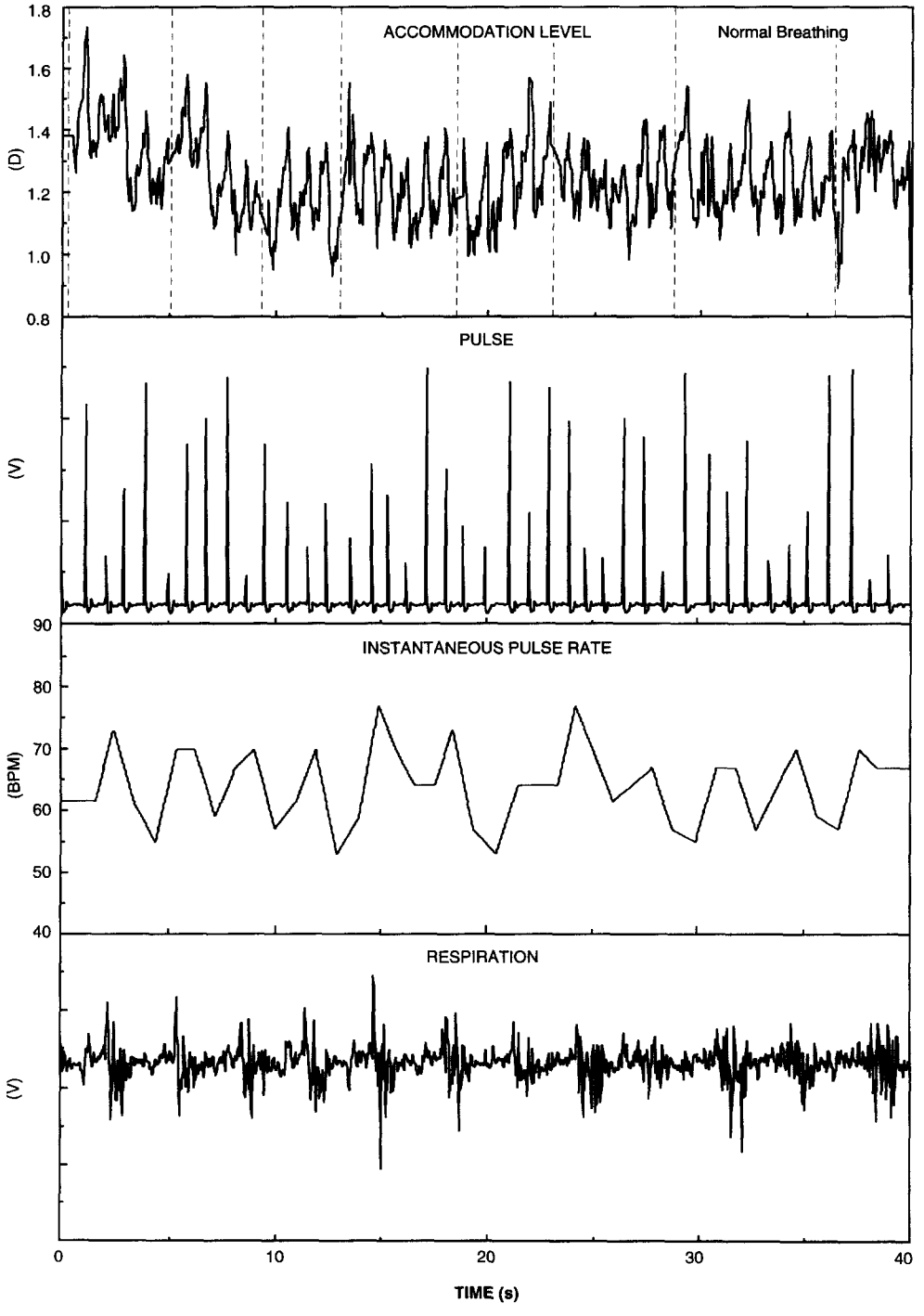

FIGURE 1. Original accommodation, pulse and respiration records for a 40 sec trial with subject AG under normal breathing conditions. Positions in the accommodation record where 8 blink artefacts were removed by an interpolation technique are indicated by a vertical dashed line. The instantaneous pulse rate (BPM is beats per minute) was calculated by measuring the time elapsed between each consecutive pulse beat.

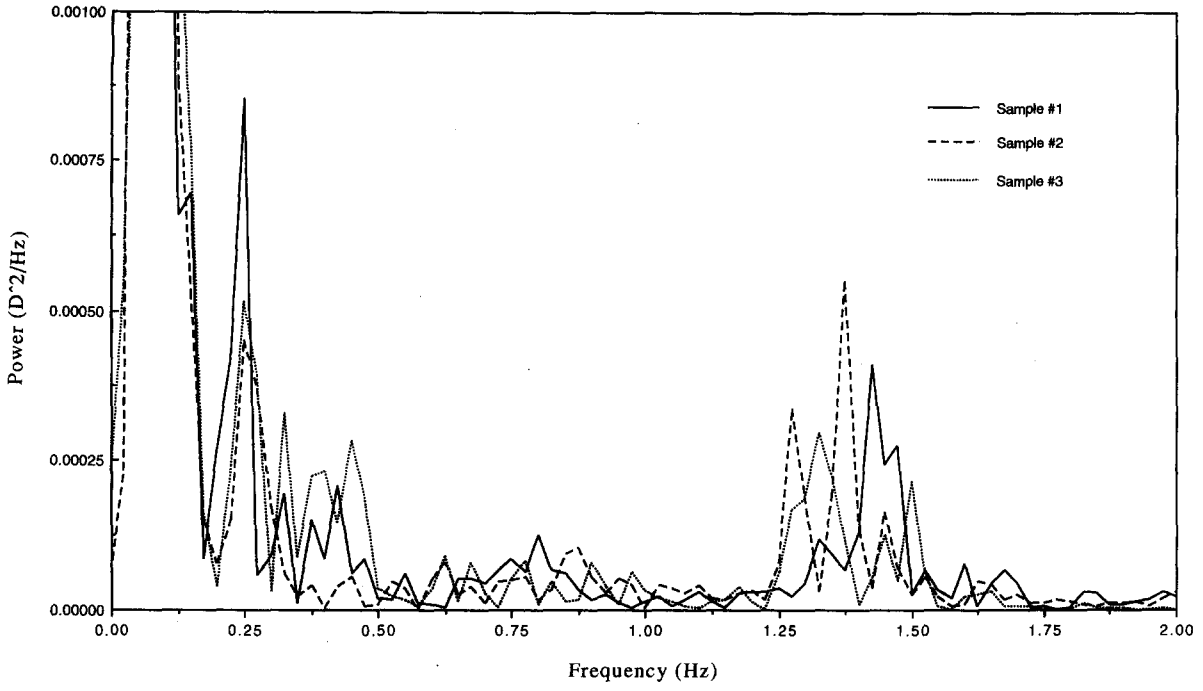

FIGURE 2. Power spectra derived from three consecutive 40 sec steady-state accommodation records. The records were acquired from the same subject (MS) under identical stimulus conditions.

data. Adams and Johnson (1991) have reported a similar criterion for acceptance of interpolated data in accommodation records.

Potential movement artefacts

The effects of pulse and respiration on eye or body movements could potentially manifest as artefacts in our accommodation measurement technique and appear as "microfluctuations" of accommodation. We therefore investigated a range of these potential artefacts.

A "model" eye was attached to the Autoref R-1 head rest and continuous recordings of "accommodation" were taken with the Autoref R-1, using a signal calibration realistic of normal eyes. There were no measurable microfluctuations in the "accommodation signal" related to vibrations in the building in which the experiments were conducted. We also left the model eye mounted on the head rest and had a subject simultaneously position themselves in the bite bar apparatus, while continuous readings were taken from the model eye. Again there were no measurable fluctuations in the model eye "accommodation signal" as a result of bodily movements associated with normal respiration, or with heavy breathing.

To investigate the relationship between antero-posterior eye movements, respiration and accommodation record, we videotaped the eye from a position perpendicular to the visual axis while simultaneously measuring steady-state accommodation/pulse/respiration during normal breathing, over a 40 sec period. We used a standard video camera with macro-zoom lens and placed a millimetre rule "in-frame" at the beginning of videotaping to provide a calibration standard. A modified half-eye spectacle frame with fixed vertical reference pin was worn by the subject to provide a reference for measurement of antero-posterior eye movements. A further reference pin was attached to the Autoref R-1 and placed "in-frame". This provided a means for detecting head/eye movements (relative to the Autoref R-1) during filming/accommodation measurement. A light emitting diode was placed "in-frame" and triggered every 10 sec via the microcomputer controlling the accommodation/pulse/respiration signal acquisition system. This provided a means of synchronising the eye position videotape with accommodation, respiration and pulse records. The resolution of this measurement technique was about 50 μm and we analysed every fourth frame of the videotape to give a 7 Hz sampling frequency for eye position.

The antero-posterior eye movements (relative to the spectacle mounted reference pin) during the 40 sec of filming, averaged about 0.25 mm and had a maximum range of 0.6 mm. The power spectrum derived from the change in antero-posterior eye position showed no frequency peaks corresponding to the major respiration or pulse related power spectrum peaks for this subject. The antero-posterior eye movements relative to the reference pin attached to the Autoref R-1 were similar in magnitude and power spectrum frequency distribution to those referenced to the spectacle reference pin. The average drift in eye position relative to Autoref R-1 was 0.15 mm, ranging up to 0.6 mm during the 40 sec. Again there was no apparent association between the power spectrum of the eye position movements and pulse/respiration cycles.

As a further method of investigating the potential effects of head/eye movements we utilized the phenomenon of eye retraction (in both eyes) associated with lid

closure in the fellow eye (Doane, 1980; Collewijn, Van Der Stein & Steinman, 1985). For two subjects (MC and JW), we recorded steady-state accommodation for 40 sec from the open right eye while the subject closed the left eye (forced blink) every 5 sec, while simultaneously holding their breath. The amount of eye retraction in the open eye, associated with lid closure in the fellow eye, was in the range of 0.5–1.5 mm in accord with the reports of Doane (1980) and Collewijn *et al.* (1985). If this regulated eye retraction had affected the accommodation measurement technique, we would expect a peak in the accommodation power spectrum at 0.2 Hz. This peak was not apparent for either subjects' data, suggesting that this degree of antero-posterior eye movement had no substantial effect on the accommodation signal recorded by the Autoref R-1. The small amount of antero-posterior eye movements associated with our apparatus using a bite bar and head strap (maximum range of 0.6 mm over 40 sec), suggests that antero-posterior eye movements were not a likely cause of microfluctuations occurring in the accommodation record measured with our apparatus.

To investigate the effect of lateral eye movements during accommodation recording, we recorded 40 sec of steady-state accommodation while a subject changed fixation in a predetermined order every 5 sec. The subject was aligned in the Autoref R-1 viewing the high contrast letter chart at 50 cm. Every 5 sec the subject was instructed to change fixation to the adjacent letter (34 min arc separation between letters). This was conducted along both the nasal and temporal meridians to a maximum of 3 deg off-axis. The data suggested that the Autoref R-1 continuous output was influenced by lateral eye movements >1 deg arc, which is substantially higher than the micromovements normally observed during steady fixation (St Cyr & Fender, 1969; Steinman, Haddad, Skavenski & Wyman, 1973).

In summary, these control experiments suggest that our accommodation measurement technique was unlikely to be significantly influenced by small eye, head or bodily movements associated with pulse or respiration.

RESULTS

Pulse, instantaneous pulse rate, respiration and accommodation

Forty-second accommodation, pulse and respiration signals were recorded for a subject (AG, aged 23 yr) who was instructed to breathe normally. The original accommodation, pulse and respiration records are presented in Fig. 1 and the derived power spectra in Fig. 3. This power spectrum reveals a series of major peaks, the lowest occurring below 0.06 Hz, the second occurring at 0.125 Hz, the third at 0.275 Hz (peak B in Fig. 3) and high frequency peaks (region A in Fig. 3). Within the high frequency peaks the major peak occurred at 1.05 Hz, with smaller amplitude peaks at 0.95 and 1.175 Hz.

The power spectrum derived from the pulse rate recording for subject AG is presented in Fig. 3. The major peak of the pulse rate power spectrum (1.075 Hz) closely matched the major high frequency peak of the accommodation power spectrum (region A in Fig. 3). There was also good correlation between the smaller adjacent high frequency peaks in the pulse and accommodation power spectra (in region A).

We further analysed the pulse rate record from subject AG, by deriving the instantaneous pulse rate. The instantaneous pulse rate was calculated by measuring the time elapsed between each consecutive pulse beat over the 40 sec sample time. Following linear interpolation between each instantaneous pulse rate data point, we derived a power spectrum, of the instantaneous pulse rate (Fig. 3). The power spectrum of the instantaneous

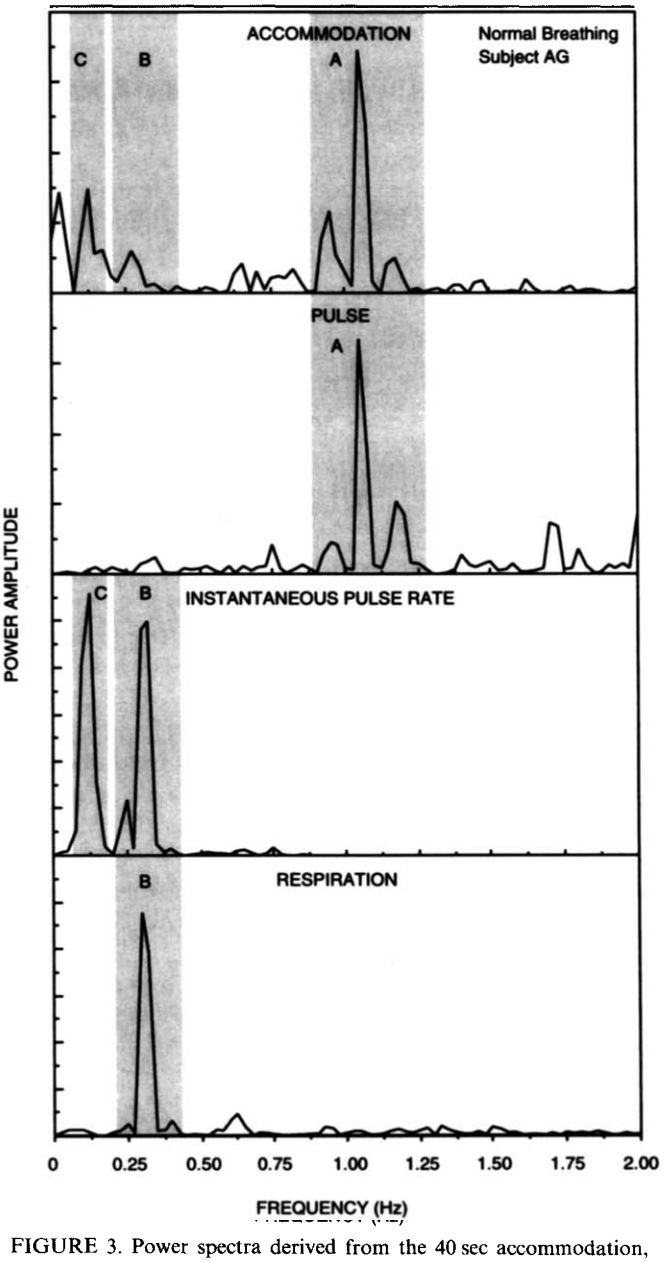

FIGURE 3. Power spectra derived from the 40 sec accommodation, pulse, instantaneous pulse rate and respiration records of subject AG under normal breathing conditions (original 40 sec records in Fig. 1). Shaded regions represent possible common frequencies between spectra.

pulse rate for subject AG showed a pair of adjacent peaks in the instantaneous pulse rate power spectrum (peaks at B), corresponding approximately to a low frequency peak of the accommodation power spectrum (peak B). There was also close agreement between the frequencies of major low frequency peaks at 0.125 Hz (peaks at C) in both the accommodation and instantaneous pulse rate power spectra.

The power spectrum derived from the respiration record for subject AG is presented in Fig 3. The major peak in this power spectrum occurs at 0.30 Hz. There was close correlation between the major respiration peak at 0.30 Hz and a major accommodation microfluctuation peak at 0.275 Hz (peak B) and a peak in the instantaneous pulse rate power spectrum at 0.325 Hz (peaks at B). The correlation between respiration and instantaneous pulse rate rhythms was also obvious in the original records for subject AG (Fig. 1).

Coherence function

A method for investigating the degree of linear dependence between two records is to calculate the coherency squared function, also called the magnitude squared coherence function or simply the coherence function (Bendat & Piersol, 1986). The coherence function is derived by calculating the magnitude squared value of the cross-spectral density function between the two records and dividing by the product of each auto-spectral density function. The following equation can be used to derive the coherence function:

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \quad (1)$$

where $\gamma_{xy}^2(f)$ equals the coherence function of the two series $x(t)$ and $y(t)$; $G_{xy}(f)$ equals the cross-spectral density function; and $G_{xx}(f)$ and $G_{yy}(f)$ equal the auto-spectral density functions.

Using finite length data the coherence is estimated by substituting in equation (1) the cross-spectral density and auto-spectral densities by their estimates. This function provides a normalized value between 0 and 1 at each discrete frequency. A coherence value of 1 indicates that the two records are linearly related at the frequency of interest, while a coherence value of 0 indicates that the two records are unrelated at this frequency. Eadie, Pugh and Winn (1995) provide a useful discussion of the interpretation of coherence functions derived from ocular signals.

It can be beneficial to divide the records into a number of segments for averaging, and to apply a smoothing function (both in the frequency domain). This improves the statistical reliability of the coherence function. If these processes are required, the estimated cross-spectral density function and the estimated auto-spectral density functions should be calculated for each segment, averaged, then smoothed before the coherence function is calculated. We divided our 40 sec records into two equal 20 sec segments and used a five-point triangular smoothing function as described above.

The 95% confidence intervals (bounds) for coherence values can be estimated using the following equation from Bendat and Piersol (1986)

$$\epsilon[\hat{\gamma}_{xy}^2] \approx \frac{\sqrt{2(1-\gamma_{xy}^2)}}{|\gamma_{xy}|\sqrt{n_d}} \quad (2)$$

where $\epsilon[\hat{\gamma}_{xy}^2]$ equals the normalized random error for the coherence value and n_d equals the number of segments multiplied by the number of smoothing points. Therefore the confidence intervals were calculated by substituting γ_{xy}^2 in equation (2) by its estimate $\hat{\gamma}_{xy}^2$ and adding and subtracting the normalized random error from the estimated coherence value.

To determine which frequencies to consider in the coherence function of two power spectra, we identified the frequency of interest in the signal considered to be the source of the rhythm. For example, in the pulse power spectrum the frequency bin corresponding to the peak of the high frequency component (pulse rate) was determined. The coherence function of pulse and accommodation was then examined at this specific frequency bin to derive the coherence value. For the coherence functions including respiration rate (accommodation–respiration rate and instantaneous pulse rate–respiration) the respiration power spectrum was examined to determine the frequency of interest (respiration rate). The respiration frequency in the instantaneous pulse rate was used as the frequency of interest in the coherence function between accommodation and instantaneous pulse rate.

The effects of regulated breathing patterns

To investigate the associations between the cardiopulmonary system and accommodation microfluctuations we simultaneously recorded accommodation, pulse and respiration for 40 sec while five subjects were instructed to: "breathe normally" for 40 sec and then "breathe rapidly" for 40 sec. The subjects remained in the bite bar for about 60 sec between each of the recordings.

The power spectra for the normal breathing conditions showed good correspondence between pulse rate and the high frequency peak of the accommodation power spectra and this was the case for all five subjects' data (Table 1). Coherence values for these high frequency peaks were all $\geqslant 0.84$, indicating a strong association between accommodation and pulse.

There was also substantial coherence between a low frequency peak at the respiration frequency for the respiration, instantaneous pulse rate and accommodation power spectra (Table 1). This coherence was apparent in four of the five subject's data with the exception of subject GA, for whom the accommodation power spectrum showed no obvious power at the respiration frequency. To illustrate the general form of the averaged and smoothed power spectra, the results for one of the subjects (subject CB) are presented in Fig. 4.

Rapid breathing produced an apparent "shift" in a low frequency accommodation peak which closely paralleled the shift in a corresponding peak of the respiration and instantaneous pulse rate power spectra. This effect is illustrated by the coherence functions between

TABLE 1. Coherence values and corresponding 95% confidence intervals for accommodation, pulse, respiration and instantaneous pulse rate time series

Subject	Pulse (Hz)	Resp (Hz)	Accom–Pulse $\hat{\gamma}^2$	Accom–Pulse Confidence int.	Accom–Resp $\hat{\gamma}^2$	Accom–Resp Confidence int.	Accom–IPR $\hat{\gamma}^2$	Accom–IPR Confidence int.	Resp–IPR $\hat{\gamma}^2$	Resp–IPR Confidence int.
Normal breathing										
CB	1.20	0.35	0.96	$(0.94 \leqslant \gamma^2 \leqslant 0.98)$	0.58	$(0.33 \leqslant \gamma^2 \leqslant 0.83)$	0.64	$(0.44 \leqslant \gamma^2 \leqslant 0.84)$	0.97	$(0.96 \leqslant \gamma^2 \leqslant 0.98)$
MS	1.65	0.45	0.93	$(0.90 \leqslant \gamma^2 \leqslant 0.96)$	{0.64}	$(0.44 \leqslant \gamma^2 \leqslant 0.84)$	{0.57}	$(0.32 \leqslant \gamma^2 \leqslant 0.83)$	0.95	$(0.93 \leqslant \gamma^2 \leqslant 0.97)$
JW	1.50	0.35	0.84	$(0.76 \leqslant \gamma^2 \leqslant 0.92)$	0.97	$(0.96 \leqslant \gamma^2 \leqslant 0.98)$	{0.95}	$(0.93 \leqslant \gamma^2 \leqslant 0.97)$	{0.90}	$(0.95 \leqslant \gamma^2 \leqslant 0.95)$
GA	1.40	0.35	0.99	$(0.99 \leqslant \gamma^2 \leqslant 0.99)$	{0.44}	$(0.06 \leqslant \gamma^2 \leqslant 0.82)$				
TD	1.45	0.45	0.94	$(0.91 \leqslant \gamma^2 \leqslant 0.97)$	0.57	$(0.32 \leqslant \gamma^2 \leqslant 0.83)$	0.79	$(0.68 \leqslant \gamma^2 \leqslant 0.90)$	0.76	$(0.64 \leqslant \gamma^2 \leqslant 0.88)$
Rapid breathing										
CB	1.25	0.95	0.97	$(0.96 \leqslant \gamma^2 \leqslant 0.98)$	0.85	$(0.78 \leqslant \gamma^2 \leqslant 0.92)$	0.88	$(0.82 \leqslant \gamma^2 \leqslant 0.94)$	0.77	$(0.65 \leqslant \gamma^2 \leqslant 0.89)$
MS	1.95	0.65	0.90	$(0.85 \leqslant \gamma^2 \leqslant 0.95)$	0.67	$(0.49 \leqslant \gamma^2 \leqslant 0.85)$	0.51	$(0.20 \leqslant \gamma^2 \leqslant 0.82)$	0.46	$(0.10 \leqslant \gamma^2 \leqslant 0.82)$
JW	1.65	0.75	0.87	$(0.81 \leqslant \gamma^2 \leqslant 0.93)$	0.82	$(0.73 \leqslant \gamma^2 \leqslant 0.91)$	0.55	$(0.28 \leqslant \gamma^2 \leqslant 0.82)$	0.69	$(0.52 \leqslant \gamma^2 \leqslant 0.86)$
GA	1.30	0.60	0.99	$(0.99 \leqslant \gamma^2 \leqslant 0.99)$	0.82	$(0.73 \leqslant \gamma^2 \leqslant 0.91)$	0.69	$(0.52 \leqslant \gamma^2 \leqslant 0.86)$	0.85	$(0.78 \leqslant \gamma^2 \leqslant 0.92)$
TD	1.65	1.55	0.85	$(0.78 \leqslant \gamma^2 \leqslant 0.92)$	0.67	$(0.49 \leqslant \gamma^2 \leqslant 0.85)$				

$\hat{\gamma}^2$ denotes the estimated coherence value and γ^2 denotes the true coherence value. Coherence values can range from 0 (unrelated signals) to 1 (linearly related signals) and were derived for the frequency of interest.

*The 95% confidence intervals for coherence values were calculated as per Bendat and Piersol (1986). Missing data is explained in the text. Accom, accommodation; Resp, respiration; IPR, instantaneous pulse rate. The coherence value is recorded in brackets where examination of the relevant region of the power specta (accommodation or IPR) revealed no obvious peak, but the power was well above background.

accommodation–respiration, accommodation–instantaneous pulse rate and respiration–instantaneous pulse rate (Table 1). The relevant power spectra for subject CB in the "rapid breathing" condition are illustrated in Fig. 5 and the corresponding coherence functions for accommodation–instantaneous pulse rate and accommodation–pulse are illustrated in Fig. 6. Data for subject TD were excluded because the "rapid breathing" frequency (1.55 Hz) was relatively close to the pulse rate (1.65 Hz) (Table 1).

Extended accommodation recordings

A consistent feature of power spectrum analyses of steady-state accommodation microfluctuations are the low frequency cycles in the range below 0.1 Hz. Given the relatively long time involved in one full period of these microfluctuation cycles, we extended our sampling time to record the accommodation, pulse and respiration signals from one subject over a period of 180 sec and then broke this signal into 4 × 45 sec signals. Because of the extended sampling time (45 sec), the resolution of the power spectra was improved to 0.022 Hz, to provide better discrimination of the low frequency components.

The subject JW, had both pupils dilated with 2.5% phenylephrine and was instructed to breathe normally in rhythm with a timer giving an audible tone every 2 sec (an inspiration and expiration every 4 sec, 0.25 Hz respiration rate). The sampling rate for the accommodation, pulse and respiration signals was 22.8 Hz. The test was repeated under identical conditions, after a few minutes break and following recalibration of the Autoref R-1. The two 180 sec sets of signals were broken into eight parts and the power spectra averaged. One of the 180 sec steady-state accommodation responses of this subject is presented in Fig. 7 and the averaged power spectra for the 8 × 45 sec signals (derived from 2 × 180 sec signals) of accommodation and instantaneous pulse rate are presented in Fig. 8.

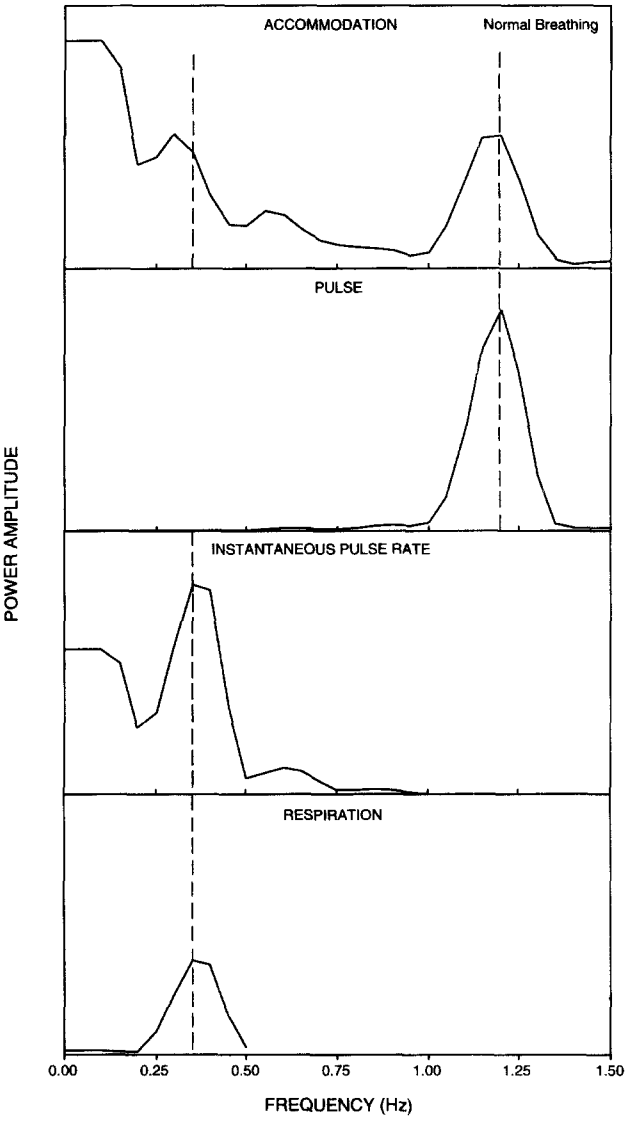

FIGURE 4. Power spectra derived from the average of 2 × 20 sec records from subject CB under the "normal breathing" condition. The relevant peaks of the pulse and respiration power spectra are traced through the instantaneous pulse rate and accommodation power spectra as dashed lines.

The respiration-related peak appeared at 0.245 Hz in both the accommodation and instantaneous pulse rate power spectra, very close to the expected frequency of 0.25 Hz (i.e. a 4 sec breathing period). The coherence value at 0.245 Hz for the instantaneous pulse rate and accommodation records was 0.65 ($0.55 \leqslant \gamma^2 \leqslant 0.75$, $n_d = 40$ derived from eight data segments and five-point smoothing). For frequencies below 0.25 Hz, there were elements of both power spectra which showed similarity. However, it is difficult to draw inferences from these data without higher resolution in the accommodation power spectrum.

DISCUSSION

High frequency components

There was a high coherence between the high frequency accommodation microfluctuations and pulse rate amongst our subjects' data, in agreement with the previous studies of Winn *et al.* (1990a) and Owens, Winn, Gilmartin and Pugh (1991). These authors have suggested three possible mechanisms through which the ocular pulse could be associated with high frequency accommodation microfluctuations: pulsatile blood flow in the ciliary body affecting ciliary ring diameter, the intraocular pressure pulse directly displacing the crystalline lens, or reduced resistance to lens elasticity with each cyclic reduction in intraocular pressure.

The rhythmic variation in intraocular pressure ranges from about 1 to 3 mm Hg and is directly associated with vascular pulse (Suzuki, 1962; Buchanan & Williams, 1985; James, Trew, Clark & Smith, 1991). Fluctuations in accommodation could arise from a pressure wave travelling through the eye, as blood enters the eye with each heart beat. In this case, the fluctuation in accommodation could result from a small anterior movement of the crystalline lens associated with each pulse. However to induce a 0.25 D fluctuation in accommodation (through lens movement alone), would require the crystalline lens to move forward (towards the cornea) by about 200 μm with each intraocular pulse beat (derived by a paraxial ray trace through an Emsley schematic eye).

Changes in total axial length associated with ocular pulse could theoretically result in small fluctuations in refractive error ("accommodation"). However studies of retinal movement (Fercher, Hu, Steeger & Briers, 1982) have demonstrated pulse related changes which appear too small to account for accommodation microfluctuations. Winn *et al.* (1990a) have also shown that when the steady-state accommodation microfluctuations were measured from an aphakic eye and phakic eye of the same subject, the high frequency microfluctuation was absent in the aphakic eye but present in the phakic eye, suggesting that the crystalline lens is likely to be the primary origin for these microfluctuations. However the mechanism which relates pulse rate with high frequency accommodation microfluctuations is as yet unknown.

Respiration component

There appears to be an association between one of the low frequency accommodation microfluctuations and respiration cycle, which has not previously been reported. One possible mechanism through which respiration could influence accommodation microfluctuations is through respiration's modulation of instantaneous pulse rate or intraocular pulse. This modulation causes heart rate to slightly increase during inspiration and reduce during expiration and is termed respiratory sinus arrhythmia (Angelone & Coulter, 1964; Bernston *et al.*, 1993). This arrhythmia is mediated through efferent parasympathetic control via the vagus nerve, but other central and peripheral factors also have complex inputs (Elghozi, Laude & Girard, 1991; Bernston *et al.*, 1993).

The sinus arrhythmia cycle is associated with both temporal modulation of pulse rate and amplitude

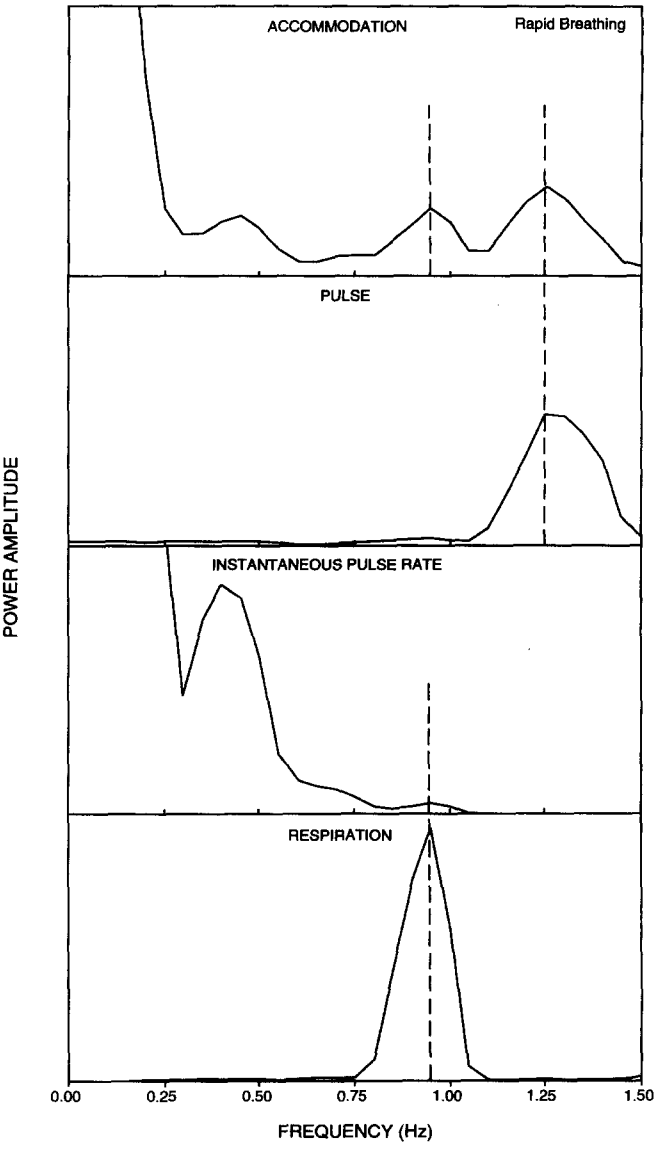

FIGURE 5. Power spectra derived from the average of 2 × 20 sec records from subject CB under the "rapid breathing" condition. The relevant peaks of the pulse and respiration power spectra are traced through the instantaneous pulse rate and accommodation power spectra as dashed lines.

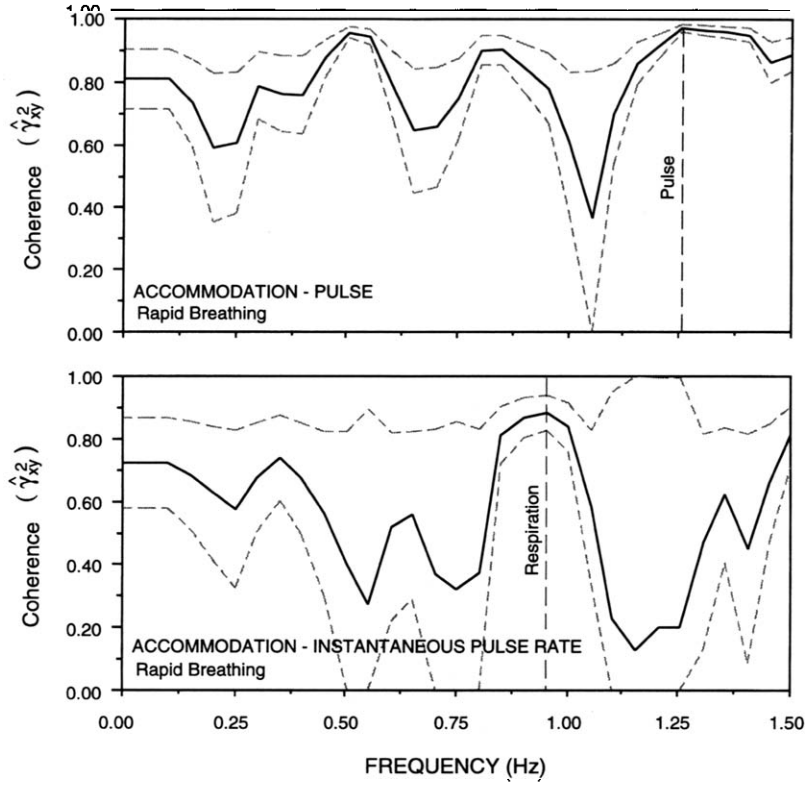

FIGURE 6. Coherence functions derived from the average of 2 × 20 sec records from subject CB under the "rapid breathing" condition (see Fig. 5). The relevant frequencies of interest in the pulse and respiration power spectra are traced through the coherence functions as vertical dashed lines. The 95% confidence intervals are plotted as lighter dashed lines around the coherence function.

modulation of blood pressure (systolic and diastolic pressure drop during inspiration and rise during expiration) (Novak, Novak, Champlain, Le Blanc, Martin & Nadeau, 1993). Sinus arrhythmia could therefore influence intraocular pulse rate and amplitude and appear at the corresponding frequency in accommodation microfluctuations.

An alternate mode of action is through the influence of the autonomic nervous system on the ciliary body. Ohtsuka, Asakura, Kawasaki and Sawa (1988) have reported a significant correlation between respiration cycle and pupil fluctuations and given the common neural innervation of the pupil and ciliary body muscles, the sinus arrhythmia cycle could simultaneously influence muscle balance in both the pupil and ciliary body. Through this potential mechanism, rhythmic changes in

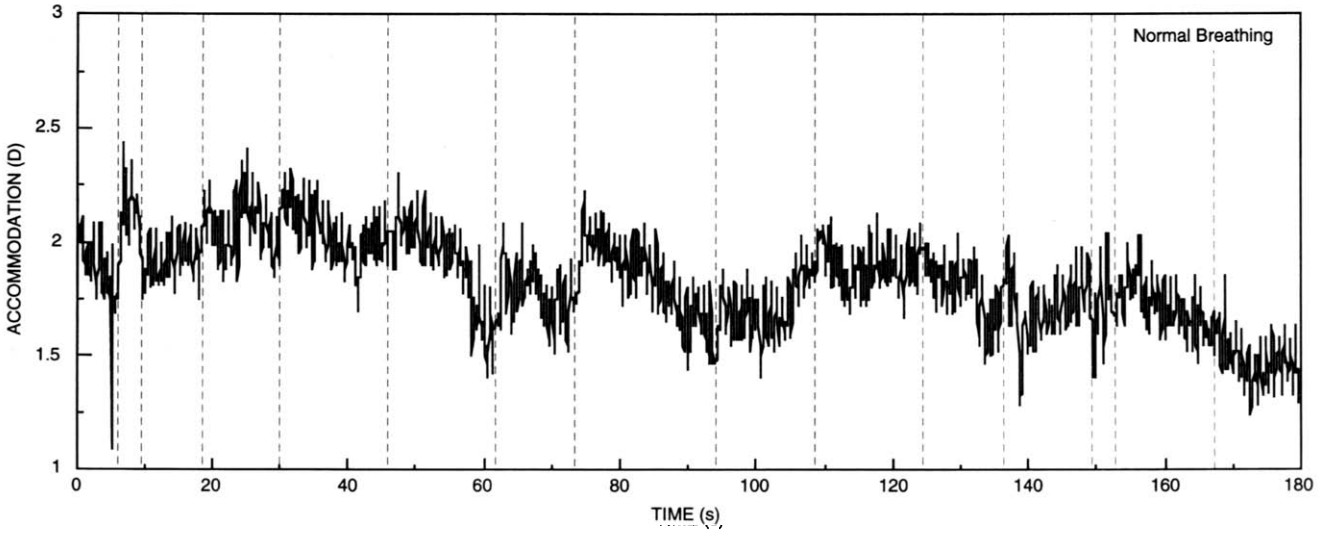

FIGURE 7. A 180 sec steady-state accommodation record from subject JW. The subject was breathing regularly on a timer set to a 4 sec period (0.25 Hz). Positions in the record where 14 blink artefacts were removed by an interpolation technique are indicated by a vertical dashed line.

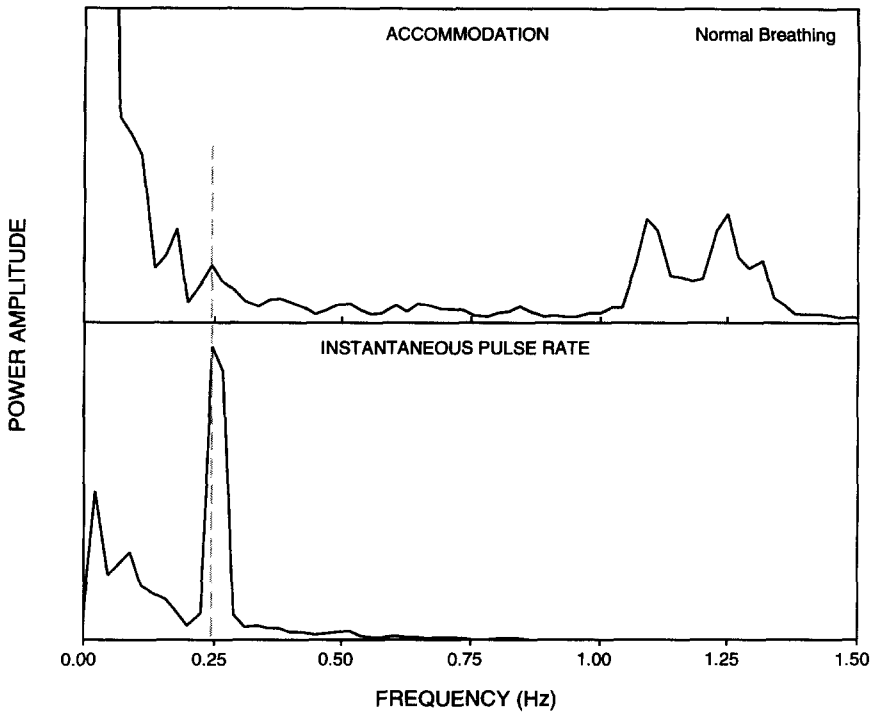

FIGURE 8. The average power spectrum derived from 8 × 45 sec accommodation records for JW, with the accompanying average instantaneous pulse rate power spectrum. The subject was breathing regularly on a timer set to a 4 sec period (0.25 Hz). The respiration frequency is evident in both the instantaneous pulse rate and accommodation power spectra close to the expected frequency (at 0.245 Hz).

parasympathetic/sympathetic balance in the ciliary body muscles could result in rhythmic fluctuations in accommodation.

When the subjects increased their respiration rate, the associated accommodation microfluctuation peak appeared to shift concurrently with respiration rate and was relatively diminished in amplitude compared with the amplitude of the high frequency peak. Similarly, the magnitude of the sinus arrhythmia peak in the instantaneous pulse rate power spectrum was diminished in the rapid breathing condition compared with the normal breathing condition. This is consistent with findings of an inverse relationship between respiratory sinus arrhythmia amplitude and respiratory frequency (Hirsch & Bishop, 1981; Raschke Hildebrandt, 1982; Novak *et al.*, 1993).

Low frequency components

The low frequency peaks (typically occurring at frequencies <0.25 Hz) of the accommodation power spectra were consistent with other studies of steady-state accommodation (e.g. Campbell, Robson & Westheimer, 1959; Winn *et al.*, 1990a; Owens *et al.*, 1991). A number of the power spectrum analyses in this study revealed apparent correspondence between low frequency peaks in the accommodation power spectrum and corresponding peaks in the instantaneous pulse rate power spectrum. Aside from sinus arrhythmia, there are other autonomic nervous system rhythms which modulate the instantaneous pulse rate and blood pressure: the Mayer wave (blood pressure rhythm) and the Traube Hering wave (minute rhythm) (Raschke & Hildebrandt,1982). The Mayer wave has a cycle time of between 6 and 20 sec (0.05–0.17 Hz) and the Traube Hering wave has a cycle time of between 20 and 100 sec (0.01–0.05 Hz). The Traube Hering wave has been shown to be present in continuous recordings of intraocular pressure (Bain & Maurice, 1959). As with sinus arrhythmia, the effect of these slow rhythms on accommodation microfluctuations could arise through the modulation of the intraocular pulse frequency or amplitude or through the direct influence of the autonomic nervous system on the ciliary muscle.

Role of microfluctuations

While the cardiopulmonary system appears to control some components of steady-state accommodation microfluctuations, these periodic changes in accommodation level may still be utilised by the accommodation system in optimizing steady-state accommodation response even though they are not under the active control of the visual system. Steady-state accommodation microfluctuations have been shown to have sufficient magnitude to be detected as suprathreshold blur by the visual system (Kotulak & Schor, 1986a; Walsh & Charman, 1988; Winn, Charman, Pugh, Heron & Eadie, 1989b) and possible roles have been suggested in the maintenance of steady-state accommodation and in the control of changes of accommodation (Alpern, 1958; Kotulak & Schor, 1986b; Charman & Heron, 1988; Walsh & Charman, 1989; Gray, Winn & Gilmartin, 1993a,b).

It has been reported in various studies that low frequency components of accommodation microfluctuations are influenced by stimulus conditions (e.g. Westheimer, 1957; Campbell *et al.*, 1959; Charman & Heron, 1988; Gray *et al.*, 1993a,b). The use of longer accommodation records (by deleting blink artefacts) would allow better resolution of the low frequency components of the microfluctuations and by simultaneously measuring the instantaneous pulse rate it should also be possible to study the relative contribution of the autonomic nervous system to these slow rhythms.

CONCLUSIONS

In the steady-state accommodation records we acquired, there were two regions of the power spectra which demonstrated an apparent association between rhythms in the cardiopulmonary system and rhythms in the steady-state accommodation response. These regions included a low frequency peak corresponding to the respiration/sinus arrhythmia cycle and a high frequency peak corresponding to the vascular pulse cycle.

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Acknowledgements—This work was funded through a grant from the Australian Research Council. We thank Dr Abdelhak Zoubir for his advice on coherence analysis and Dr Bernard Gilmartin for his comments on the manuscript.